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A SMALL-SCALE FIELD CHECK ON THE FISHER–LEHMANN AND BAKKER–LE HEUX CLIFF DEGRADATION MODELS

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ABSTRACT

The paper considers the development of initially straight, steep rock cliffs, bounded above and below by horizontal surfaces, in which basal debris removal is zero and degradation occurs by the weathering away of fine debris from the cliff face to form a scree at its foot. Of the slope degradation models available, the two earliest and simplest, namely the Fisher–Lehmann and the Bakker–Le Heux models, are regarded as most relevant and are briefly summarized. The main purpose of the paper is to check the predictions of these models, particularly with regard to the shape of the rock surface buried beneath the scree, against field data. Such data are sparse. It is concluded that the best field case currently available, despite its small scale, is that provided by the 1·75 m deep ditch which forms part of the experimental earthwork in the chalk on Overton Down, Wiltshire. The predictions of the two models are checked against field measurements made of the stage of degradation reached on each face of the ditch by July 1968, eight years after its excavation. These stages were influenced to different degrees by the presence of a surface turf layer. For the NE face, where this influence was least, the agreement of the predictions of the Fisher–Lehmann model with the actual rock profile is excellent and that of the Bakker–Le Heux model only marginally less so. For the SW face, as expected, the agreements are somewhat less close. These results may be to some extent fortuitous because of the influence of the turves and because the scree slopes tend to be concave rather than rectilinear, as assumed. Also, the free faces decline with time in a manner intermediate between those assumed in the two models. Larger scale field checks are clearly desirable before firm general conclusions can be drawn.

Rates of crest recession for the Overton Down ditch are logarithmic with time after a very rapid initial phase. Extrapolation from the early phase of this logarithmic behaviour leads to a close estimate of the time needed for the slope to develop fully. The associated ultimate crest recession is also closely predicted by equations derived from both models.

KEY WORDS: chalk; abandoned cliff; excavated slope; slope degradation models; Fisher–Lehmann; Bakker–Le Heux; Overton Down Experimental Earthwork; ditch; bulking; weathering; buried rock surface profile; free face; recession rate; ultimate recession.

INTRODUCTION

It is well over a century since Fisher (1866) published his model for the degradation of an abandoned, initially vertical chalk cliff, with no bulking of the debris, and over 60 years since Lehmann (1933) generalized this model to embrace an initial straight slope of any inclination with any degree of bulking. However, while some qualitative support for these models has been drawn from field observations, no quantitative field checks appear to have been made. This is doubtless principally because of the difficulty of establishing the initial shape and inclination of cliffs that have degraded in this way and, to a lesser extent, the practical problem of determining the form of the buried surface of the intact rock beneath the accumulated scree.

CLIFF DEGRADATION MODELS

Of the many such models available (e.g. Scheidegger, 1961; Carson and Kirkby, 1972; Young, 1972; Andrews and Hanks, 1985), the two earliest and simplest are considered to be the most relevant here, namely those of Fisher (1866) and Lehmann (1933), and Bakker and Le Heux (1947). Consideration is also limited to the case where no material is supplied to the slope from above its crest, or removed from its toe.

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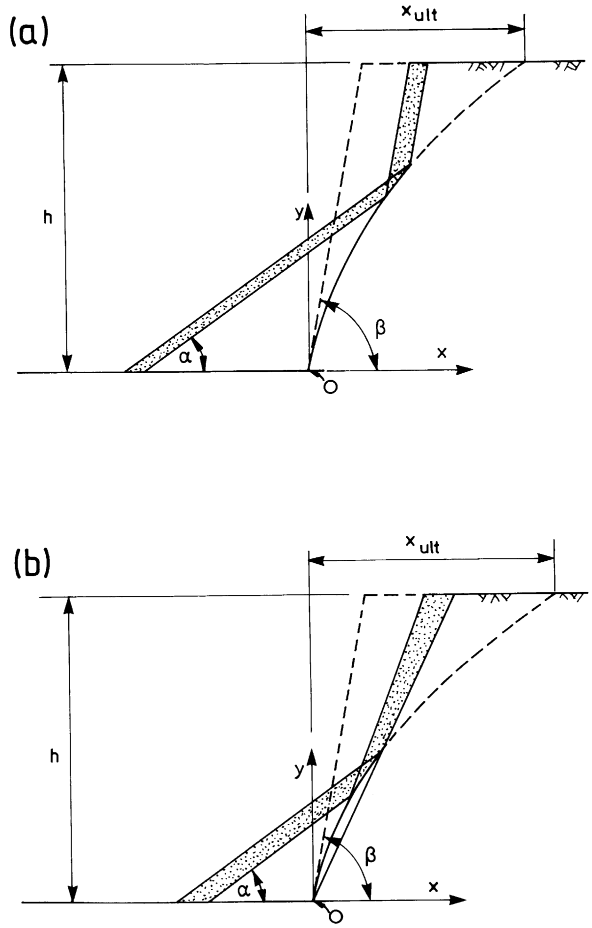


Figure 1. Cliff degradation models considered: (a) Fisher–Lehmann and (b) Bakker–Le Heux

The essential assumptions of the Fisher–Lehmann model (Figure 1a) are that:

(1) an initially straight slope of uniform material of inclination β exists, steep enough for debris removal not to be transport-limited (Carson and Kirkby, 1972);
(2) the slope has horizontal ground at its foot and crest;
(3) no standing water is present at the foot;
(4) in a given time, weathering produces an equal retreat of all parts of the exposed free face by the falling away of fine debris, which can be approximated to theoretically by infinitesimal increments; more major falls, on discontinuities for example, are not considered;
(5) the resulting debris accumulates contemporaneously at the cliff foot as a rectilinear scree of constant angle α (<β);
(6) beneath the accumulating scree, the intact rock surface is protected from further weathering, while the exposed rock face above continues to weather and retreat. Thus, with time, a convex-outward shape is produced in the surface of the intact rock beneath the scree;
(7) in the limit, the original cliff develops into a straight slope inclined at the scree angle, α, to which, in its last-formed upper part, the underlying convex rock core is tangential.

The Fisher–Lehmann model yields the following expression for the equation of the convex curve of the rock core (Lehmann, 1933):

$$x = k(l + m)\ln[m/(m - y)] - ky \tag{1}$$

where $m = h/c$; $k = (a - ac - b)/c$; $l = bh/(a - ac - b)$; $a = \cot \alpha$; $b = \cot \beta$; $1 - c$ = volume of rock/volume of debris; x, y, h, α and β are as defined on Figure 1a.

The assumptions for the Bakker–Le Heux model differ in only one respect from those given in (1) to (7) above, in that the cliff retreat in (4) is taken to increase rectilinearly with height above the toe (Figure 1b).

The Bakker–Le Heux model yields the following expression for the equation of the convex curve of the rock core (Bakker and Le Heux, 1947):

$$x = ay - (a - b)y \, [(h^2 + (1 - 2c)y^2)/h^2]^{(c-1)/1-2c} \tag{2}$$

for $c \neq 0{\cdot}5$ (Scheidegger, 1970), with symbols as defined before.

Both of these models can, if required, readily be modified, by changing the value of c, to allow for a given rate of increase in the scree volume as a result of the input of external materials, or a decrease in this volume as a result of basal removal.

To approximate to the requirements of the model, the slope-forming material should be reasonably uniform and sufficiently strong and coherent to stand initially in a steep slope, without being prone to massive modes of failure, and to break down under weathering to form relatively fine, cohesionless debris. The chalk of southern England, which stimulated Fisher's original concept, is probably one of the materials most nearly fulfilling these criteria. The model is not restricted to chalk; Lehmann (1933), for example, discusses sandstone, dolomite and metamorphic rocks in this connection.

QUARRY FACES, DEFENDED AND ABANDONED CLIFFS

The location of the chalk quarry 'in the neighbourhood of Lewes', Sussex, referred to by Fisher (1866), is not known. If initial slope geometries could be determined, degraded old quarry faces might offer good opportunities for checking the predictions of cliff degradation models.

Defended cliffs, such as those in chalk in the Rottingdean area and behind Dover harbour, could provide opportunities for such checks on the present models but, even where the initial geometry is known, these generally suffer from the removal of unknown amounts of debris from their bases. In cliffs of chalk abandoned naturally during the post-glacial period, either along river valleys or on the coast, degradation has proceeded further but the problem of their initial geometries remains. Older abandoned interglacial cliffs of chalk are exposed, for example, at Sewerby, Yorkshire, Black Rock, Sussex, and Sangatte, France. Since abandonment, these cliffs have been subjected to major inputs of external materials comprising blown sand, loess, periglacial solifluction (especially where, as at Black Rock, the hinterland slopes down appreciably to the cliff crest) and, in the case of Sewerby, till. The extra protection thus provided may have rendered these profiles generally steeper than the present models would indicate.

EXPERIMENTAL EARTHWORKS IN BRITAIN

A further group of steep soil or rock faces, subject to free degradation (Hutchinson, 1967), is provided by experimental earthworks constructed for archaeological purposes. Reviews of those in the British Isles have been given by Proudfoot (1964), Fowler (1984), Reynolds (1989), Crabtree (1990) and Bell *et al*. (1996). Of chief interest here is the experimental earthwork in chalk on Overton Down, Wiltshire.

The experimental earthwork on Overton Down, Wiltshire

This earthwork was built during July 1960, on Overton Down (Grid Ref. SU 1294 7067), in chalk with flints at an elevation of about 232 m OD. It was completed by 28 July (Jewell, 1963). According to Kerney (1963), the Overton Down trench lies either near the top of the *Micraster cortestudinarium* Zone or near the base of the *Micraster coranguinum* Zone of the Upper Chalk. The area has never been glaciated but has been subject to severe periglacial conditions (Everard, 1963).

The planning, design, construction and initial state (Figure 2) of this earthwork are described by Jewell (1963). It consisted of a 30·5 m length of ditch and bank of uniform cross-section aligned approximately NW to SE, the bank being situated on the NE side of the ditch. The ground profile at the site consists of 0·12 m of turf

Figure 2. Overton Down Experimental Earthwork: photograph from the NW of initial state in July 1960 (Copyright Experimental Earthworks Committee)

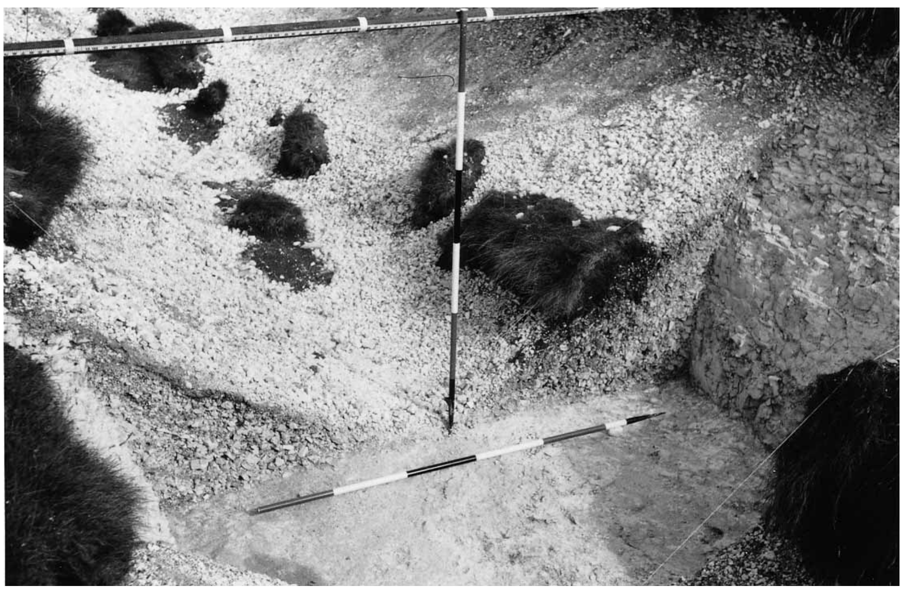


Figure 3. Overton Down Experimental Earthwork: photograph from the SE of stage of degradation reached in July 1964, after four years (Copyright Experimental Earthworks Committee)

and topsoil, over 0·11 m earth and flints, over 0·33 m of weathered chalk followed by 'unweathered chalk' (in fact, the whole profile will have suffered some degree of weathering). The regional dip is about 2° to the SSE (Crabtree, 1971).

The designed ditch profile was as follows: at the ground surface, a width of 3·05 m for a depth of 0·23 m, whence it diminished uniformly to a bottom width of 2·44 m at a further depth of 1·52 m, giving a total design depth of 1·75 m and side slopes (below the 0·23 m vertical cut) of 78·7°. The constructed and designed profiles generally agreed to considerably less than 2·5 cm, though where occasional blocks of hard chalk or flint projected or were removed, deviations of as much as 2·5 cm did exist.

Following the initial survey of the ditch and bank in July 1960, the progress of degradation was determined by repeating such surveys at prescribed intervals on excavated cross-sections. The accuracy of these field

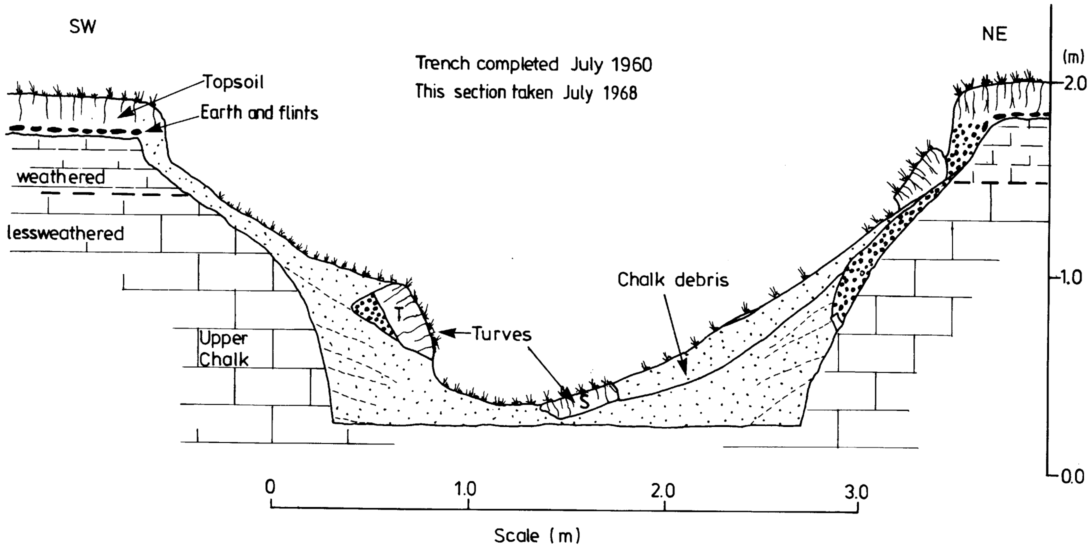


Figure 4. Overton Down Experimental Earthwork: surveyed cross-section of July 1968, after eight years (Crabtree, 1971). The bank is behind the NE face

measurements was ±1·25 cm (K. Crabtree and P. J. Fowler, pers. comm.). Five stages of development have so far been surveyed, in 1962, 1964, 1968, 1976 and 1992. The cross-sectional profiles of 1962 and 1964 (Figure 3) are reported by Jewell and Dimbleby (1966) at a scale of 1:109 and that of 1968 by Crabtree (1971) at 1:30. The cross-sections of the ditch and bank surveyed in 1968, 1976 and 1992 are given, at 1:40, by Bell *et al.* (1996). From at least 1964 onwards, some asymmetry is evident in the developing ditch cross-section, as discussed below.

The July 1968 cross-section (Crabtree, 1971) (Figure 4) was located in the central part of the earthwork at 'Pole VI' (Jewell, 1963; fig. 8), where degradation of the ditch was well advanced. But although Jewell's (1963) review of theoretical models was noted, no attempt was made to relate the observed cross-sectional profile to these. The 1976 and 1992 cross-sections (Bell *et al*., 1996) exhibit continuing degradation, but with increasing interference between the two sides of the ditch.

The experimental earthwork at Wareham, Dorset

Following the successful construction of the Overton Down Experimental Earthwork, a second earthwork was built in 1963. To provide a contrast with the alkalinity of Overton Down, it was sited on acidic sands near Wareham (Grid Ref. SY 911 923). The ditch was 1·7 m deep, with a base width of 2·39 m and side slopes of around 80°. Cross-sections have been excavated and measured at periods of up to 17 years after construction (Evans and Limbrey, 1974; Bell *et al*., 1996).

The intention was to build this earthwork entirely in sand and a preliminary test pit confirmed such a profile. However, excavation of the ditch revealed the strata to be current-bedded sands with sloping lenses of pipe-clay. One of the latter extends about half the length of the ditch. Accordingly, while this case does provide a broad qualitative illustration of the type of behaviour illustrated in Figure 1, it does not readily provide a quantitative check on models of slope degradation.

CHOICE OF SECTION AND PARAMETERS AT OVERTON DOWN

The Fisher–Lehmann and Bakker–Le Heux models apply to single cliffs. They will apply to ditches, therefore, only while there is no mutual interference between the toes of the opposing scree slopes. Once such interference occurs, the boundary conditions change. The effect of this on the form of the slope of intact rock beneath the

debris is to introduce a discontinuity, marking the commencement of a steepening in the upper part of the 'trumpet-mouthed' profile. This situation, which is common in archaeological ditches, will be dealt with in a separate paper.

In the 1962 and 1964 (Figure 3) cross-sections at Overton Down, the toes of the opposing scree slopes barely impinged on one another. In 1968 (Figure 4), the scree toes met over a depth of 10 cm, but this is probably due largely to the effects of slope wash and shallow sliding in the lower parts of the scree slopes, and to the presence of turves, and is not considered to have significantly affected the development of the convex rock profile. By 1976, interference between the toes of the scree slopes was becoming more marked and, furthermore, material from the bank behind the NE face was beginning to enter the ditch, which was not the case up to and including 1968 (Fowler, 1989; Crabtree, 1990). Thus, the 1968 section is regarded as being the most appropriate against which to check the predictions of the slope degradation models. In addition, a large-scale (1:12) version of this section was kindly provided by Dr P. J. Fowler.

In the present context, the worst feature of the Overton Down site is the presence of the 12 cm thick turf and topsoil layer. From time to time this has broken away in large pieces, which have tended to modify the degradation pattern which would have been followed by the chalk alone. From the 1964 and 1968 (Figure 4) sections, it appears that both faces of the ditch were sometimes affected in this way, but the NE face rather less so than the SW. Thus, the NE face of the ditch is considered to provide the better check for the slope degradation models. For completeness, both faces are analysed.

NE face of the ditch

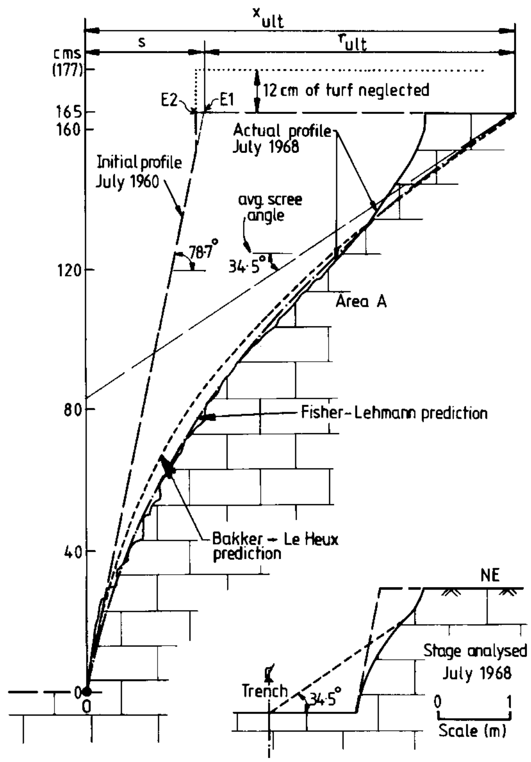
The initial overall depth of the ditch was determined to be 1·74 m (Jewell, 1963). This value has been slightly modified, to 1·77 m (Figure 5a), to take account (by +2 cm) of the crossfall of about 1 in 26 of the natural ground from NE to SW and (by +1 cm) of a slight deviation of the ditch bottom from the horizontal. Neglecting the 12 cm thick turf and topsoil layer and considering the underlying 11 cm of earth and flints to be part of the chalk, gives the total effective height, h (Figures 1 and 5a), as $1{\cdot}77-0{\cdot}12=1{\cdot}65$ m. The initial crest of the ditch was, as originally specified, 0·305 m on the NE side of the vertical through the slope toe (point O on Figures 1 and 5a), descending vertically for 0·11 m from the notional new top surface at the base of the turf. The initial inclination of the ditch side, of 78·7°, is taken to extend linearly up to the notional new top surface, the small wedge of earth and flints (12 cm^2 in sectional area) on the ditch side of this line being neglected (Figure 5a).

The scree slope below the NE face in 1968 was not linear but concave outwards, reducing in inclination from about 36° in its upper parts to about 18° in its lower (Figure 4). Thus, the assumption of a straight scree slope in the Fisher–Lehmann and Bakker–Le Heux models is not met consistently in this case. The more rectilinear profiles during build-up, shown by the various stone lines (Figure 4), varied from around 22 to 36°. The excavations up to 1968 showed that this primary fill is made up of five bands of relatively coarse chalk rubble separated by layers of fine, humic-stained debris (Crabtree, 1971). It was suggested that the banding is an annual phenomenon, with the coarser bands resulting from frost weathering in the winters and the fine layers from summer sedimentation (Jewell and Dimbleby, 1966; Bell, 1990). The less inclined lower scree probably results from a combination of the rolling down of larger fragments, shallow sliding movements under conditions of heavy rain, and slope-wash (Jewell and Dimbleby, 1966). Bearing these factors in mind, an average value of 34·5° has been chosen for α (Figure 1). As shown in Figure 5a, with this inclination the corresponding scree toe does not quite reach to the centre-line of the ditch.

A further important parameter is the bulking factor for the debris. From calculations of the volumes of rock weathered away and of correponding volumes of debris produced in the measured cross-sections, Jewell and Dimbleby (1966) give factors of 1·62 for the 1962 situation and 1·90 for that in 1964, turf being excluded in each case. For 1968, Crabtree (1996) reports a factor of 1·663, but including turves and organics. From measurements obtained by breaking chalk into buckets, Jewell (1963) found a factor of 1·75. The average factor for chalk compacted in the bank was 1·42 (Jewell, 1963).

In the present study, an estimate made on the measured 1968 section of the NE slope, to the lowest point of the ditch infill rather than to the centre-line of the ditch, gave a bulking factor of 1·67, excluding turf. The corresponding value of c is thus 0·4.

(a)



(b)

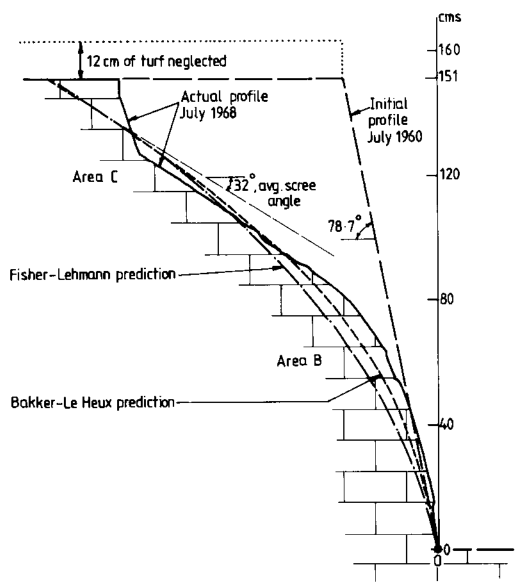


Figure 5. Overton Down Experimental Earthwork: surveyed cross-sections of July 1968. Reconstructed initial profile, and the solid rock profile measured in July 1968 compared with the predictions of the Fisher–Lehmann and Bakker–Le Heux cliff degradation models: (a) for the NE face and (b) for the SW face

SW face of the ditch

Because of the method of excavating the ditch using a template (Figure 2), and the crossfall of the original ground surface to the SW, the initial depth of the SW face is about 11 cm less than that of the NE face and, accordingly, no significant vertical cut is left at the top of the section (Figure 5b). The overall initial depth was 1·65 m (Jewell, 1963). This has been modified slightly (by −2 cm) to account for the crossfall. Thus, the total effective height, h, after deduction of the 12 cm turf and topsoil layer, is 1·51 m (Figures 1 and 5b).

The 1968 bulking factor, determined here in the same way as for the NE face, is 1·42 (comparable to Crabtree's (1996) value of 1·469 including turves and organics). Thus c is 0·30. The average scree angle, α, is difficult to determine for 1968 because of the presence of a large turf, T (Figure 4), but was previously fairly rectilinear. It is estimated at 32°. With this angle, the corresponding scree toe does not quite reach to the centre-line of the ditch. As before, β is 78·7°.

COMPARISON OF MODEL PREDICTIONS WITH FIELD BEHAVIOUR AT OVERTON DOWN

NE face of ditch

Figure 5a shows the initial ditch profile and the profile of the intact chalk beneath the scree in July 1968, after eight years of degradation. For comparison with the latter, the predicted final rock profiles are also shown, for both the Fisher–Lehmann and the Bakker–Le Heux models. These are calculated for the geometry and parameters arrived at above, namely $h = 1{\cdot}65$ m, $\alpha = 34{\cdot}5°$, $\beta = 78{\cdot}7°$ and $c = 0{\cdot}4$. The procedure followed was to plot first the profiles predicted by the two models and then the actual rock profile. No subsequent adjustments to improve the fit were carried out.

As can be seen, the agreement of the Fisher–Lehmann curve with the field data could hardly be bettered. The Bakker–Le Heux curve is a slightly less good fit, being a little too convex, but its departure from the field data does not exceed 4 cm (2·4 per cent of h). The lack of fit of both theoretical curves in the uppermost 0·3 m of the section merely reflects, of course, the fact that in 1968 the development of the slope was incomplete.

It seems reasonable to argue, following Scheidegger (1970), that the degree of denudation in a cliff is likely to be greater at the top than at the bottom, particularly when, as here, the top is composed of more weathered material: accordingly, of the two degradation models considered here, that of Bakker–Le Heux might be expected to be closer to reality. The fact that this is not borne out for the NE profile of the rock core in 1968 may be due partly to microclimatic effects. For example, unlike an open cliff-line, the ditch forms a closed depression and may therefore have acted as a frost hollow, with cold air collecting in the ditch and causing stronger frost weathering in its lower parts.

The influence of the turves which descended into the ditch is hard to quantify. Reference to the section of the NE face of the ditch in 1964 (Jewell and Dimbleby, 1966, fig. 1), shows that a turf then occupied the middle of the scree slope, tending to cause a build-up of debris above it and a corresponding depletion below it. This turf, S, had moved to the foot of the scree by July 1968 (Figure 4). The associated transient build-up of debris in the upper slope in and around 1964 would have tended to reduce the amount of denudation there. Thus, without the effect of this turf, the slight lack of fit between even the Fisher–Lehmann curve and the actual rock profile that is discernible in Area A of Figure 5a, perhaps due to the presence of more weathered chalk in that area, is likely to have been more marked.

This case indicates that both the models considered give predicted buried intact rock profiles in good agreement with reality, with the Fisher–Lehmann model being particularly accurate. However, in view of the deviations from the model assumptions caused chiefly by the turves and the sometimes concave scree profile, these agreements may be somewhat fortuitous. It would, in any case, be inappropriate to draw firm general conclusions from this one, small-scale field test.

SW face of the ditch

For the SW face of the ditch in July 1968, the initial profile and the profile of the intact chalk beneath the scree, after eight years of degradation, are given (Figure 5b). Again, the predicted final rock profiles are shown

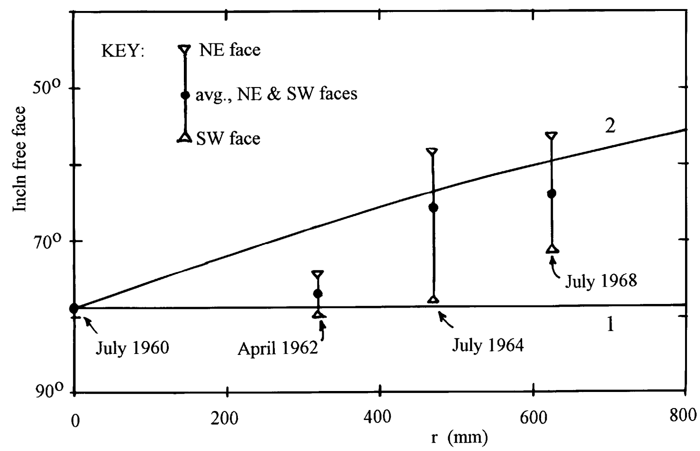


Figure 6. Overton Down Experimental Earthwork: rough observations of variation in inclination of free faces of ditch with amount of crest recession. 1, Relationship assumed in Fisher–Lehmann model; 2, relationship assumed in Bakker–Le Heux model

for both the Fisher–Lehmann and the Bakker–Le Heux models, using the parameters $h=1{\cdot}51$ m, $\alpha=32°$, $\beta=78.7°$ and $c=0{\cdot}3$.

As expected, the agreement between the predicted and the actual rock profiles is less close here, though the maximum horizontal departures of the theoretical curves from the field data are not above 11·3 cm (7·5 per cent of h) for Fisher–Lehmann and 7·0 cm (4·6 per cent of h) for Bakker–Le Heux, with the latter again predicting the greater convexity and thus being closer to reality in this case.

The more convex protusion of the actual middle and lower rock profile (Area B, Figure 5b) would appear to be largely due to the greater and earlier protection afforded by the descent of the major turf lump (T, Figure 4) although, as discussed below, there may have been a small contribution from expansion of the *in situ* chalk following the excavation of the ditch and later weathering. The greater-than-predicted retreat of the chalk face in the upper part of the profile (Area C, Figure 5b) is probably due to the presence of more weathered rock there, resulting partly from the fall in ground level towards the SW.

Free faces of the ditch

In the Overton Down ditch, it is difficult to check the extent to which the actual free faces conform with those assumed in the Fisher–Lehmann and Bakker–Le Heux models (Figure 1) because of the tendency of the turf and the uppermost chalk to overhang. By neglecting these effects, however, it has been possible to recover a very rough indication of values for the inclinations of the free faces in the period 1960 to 1968. These are plotted, for the NE and SW faces and the average of these, against the amount of crest recession in Figure 6, with the relationships assumed in the above two models also shown.

It appears that the averages of the field observations lie between the assumptions of the two models and generally nearer to that of Bakker–Le Heux.

Asymmetry of the ditch

This asymmetry is evident for the 1968 situation from Figure 4. In quantitative terms, the volumes of *in situ* chalk lost per metre run by July 1968 on the NE and SW faces of the ditch were, respectively, 0·421 and 0·376 m^3. The corresponding scree volumes (without turves) were 0·702 and 0·534 m^3. These observations suggest that the greater degree of denudation occurred on the NE face. However, crest retreats on the NE and SW faces by 1968 were around 0·63 and 0·70 m, respectively, and the corresponding average inclinations between the chalk crest and toe were about 59° and 54·5°. These apparent anomalies may arise from the superior height of the NE face and the presence of a greater thickness of more weathered chalk in the upper part of the SW face (Area C, Figure 5b), already noted.

Reasons for this asymmetry are discussed by Crabtree (1971) who relates it to aspect, with increased rainbeat from the W to SW prevailing winds and greater freeze–thaw action on the NE (SW-facing) face being probable contributory factors. The influence of frost weathering on recession rates in chalk is emphasized by Lautridou *et al*. (1983).

Post-excavation changes in the rock profile beneath the scree

In the lower 0·4 m of the profile of the SW face of the ditch, the actual 1968 rock face protrudes up to about 2 cm beyond the original line of the cut face. As this protrusion is general rather than local, it seems likely to have resulted from frost action or, as suggested by Crabtree (1971), from relaxation and expansion of the cut rock face following excavation. A similar, but smaller protrusion is also present in the lower part of the NE cut face.

In addition to frost and other weathering of the exposed cut faces, inherent in the two slope development models considered, Bell *et al*. (1996) summarize evidence for modification of the rock profile of the ditch by biological and physical activity. In particular, frost heave appears to have affected the ditch floor, slightly by 1968 and significantly by 1992 when a rise of 0·1 m had occurred near the ditch centre (see earlier comments on microclimate).

Considerable further changes to the rock profile beneath the SW face of the ditch are suggested by a comparison of the 1968 and 1992 sections (see Bell *et al*., 1996, fig. 14.2). Although these two sections are not exactly coincident, it does appear that between these two dates a further retreat of the middle to upper parts of the chalk face, beneath the scree, of up to about 0·4 m occurred.

These observations indicate that in this small-scale ditch in chalk, susceptible as it is to various types of physical, chemical and biological weathering, the assumption that the developing scree protects the underlying rock core from further weathering is not entirely justified. However, such changes were very small in the first eight to ten years after excavation of the ditch and are not considered to have impaired significantly the value of the 1968 section for the present field check.

RATE AND TOTAL AMOUNT OF CLIFF RECESSION

The crest retreat of the NE face of the Overton Down ditch is shown against natural time (Figure 7a) and against log. time (Figure 7b). The curves after 1968 are shown with broken lines because, as noted earlier, some interference of scree toes and slight input of material to the ditch from the bank was then occurring. Between July 1960 and April 1962, the average rate of crest retreat was 15·2 mm/month, between then and July 1964, 5·6 mm/month, between then and July 1968, 3·2 mm/month, and from then to July 1976, 1·3 mm/month. The overall average rate of crest recession between July 1960 and July 1976 was 46·8 mm/year. The high early rates of retreat are doubtless a reflection of the generally weathered and broken nature of the chalk, the high initial slope angle and the disturbance and stress relief inevitably associated with excavation. The lower rates of retreat after about 1964/65 reflect the near-completion of the primary filling and the burial of most of the free face, noted by Crabtree (1971; 1990). The plot of Figure 7b shows that, after an initial very rapid phase, the rate of crest retreat is approximately logarithmic, as suggested elsewhere for the associated rate of ditch infilling by Cornwall (1958).

The estimated ultimate amount of crest retreat, r_{ult}, is readily obtained from the plots of Figure 5, or from Equations 1 and 2 by putting $y=h$ and subtracting s. Thus for Fisher–Lehmann:

$$r_{ult}=(\cot\alpha-\cot\beta)\,(1-c)\,h/c\,[1/c\,\ln(1-c)^{-1}-1] \tag{3}$$

and for Bakker–Le Heux:

$$r_{ult}=(\cot\alpha-\cot\beta)\,h\,\{1-[2(1-c)]^{(c-1)/(1-2c)}\} \tag{4}$$

For the more representative NE face (Figure 5a), these expressions give r_{ult} values of 0·862 and 0·874 m, respectively, from point E1 (or 0·884 and 0·896 m from point E2). An estimate of the total time, from July 1960, required to reach these ultimate degradation profiles can be obtained by extrapolating a plot of the earlier part of the logarithmic relationship (Figure 7b) to these r_{ult} values. This indicates about 31 years (i.e. 1991) using Fisher–Lehmann or about 33 years (i.e. 1993) using Bakker–Le Heux. The 1992 survey (Bell *et al*., 1996)

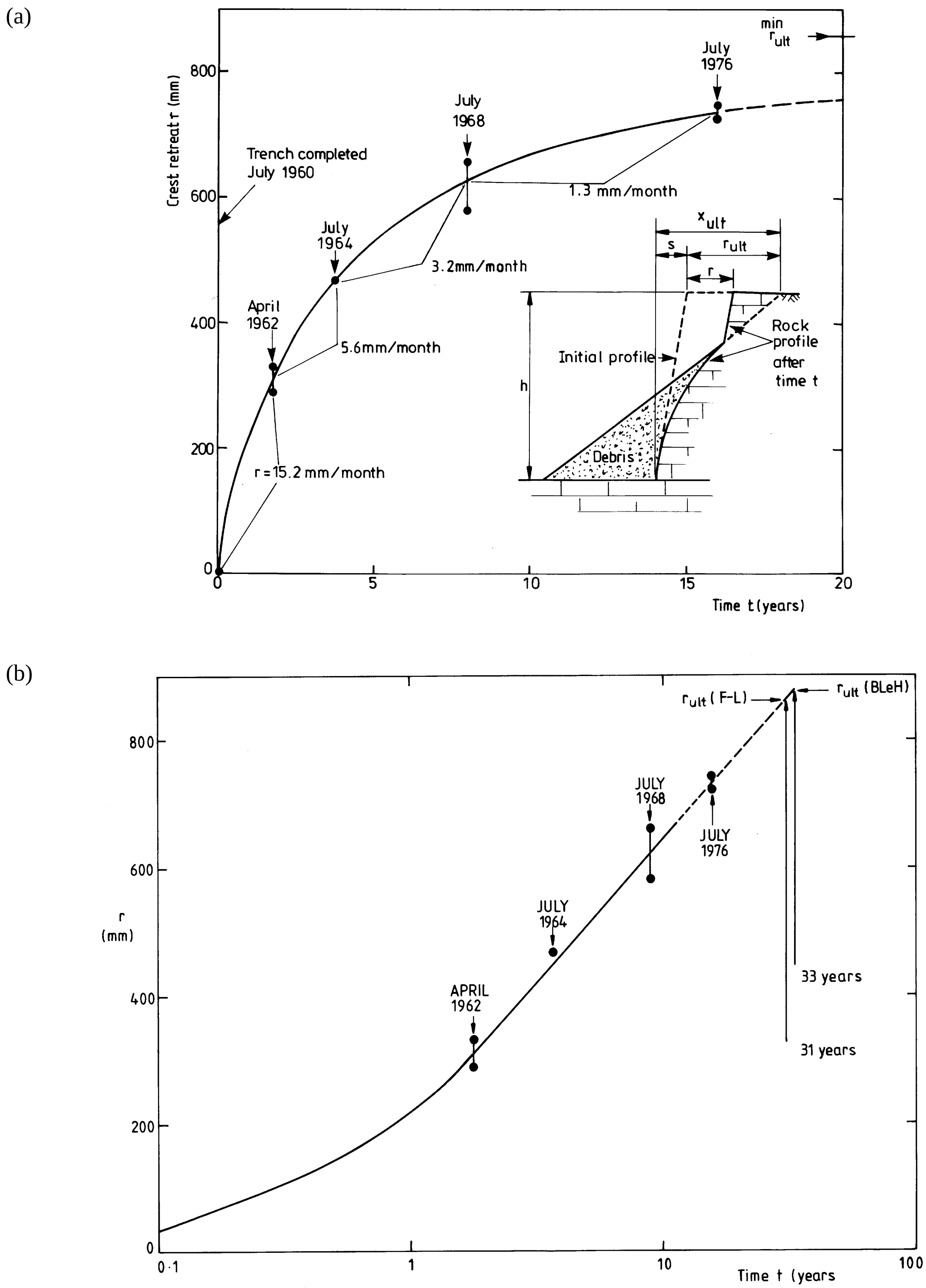


Figure 7. Overton Down Experimental Earthwork: rate of crest retreat on NE face: (a) plotted against time on a natural scale and (b) plotted against time on a logarithmic scale

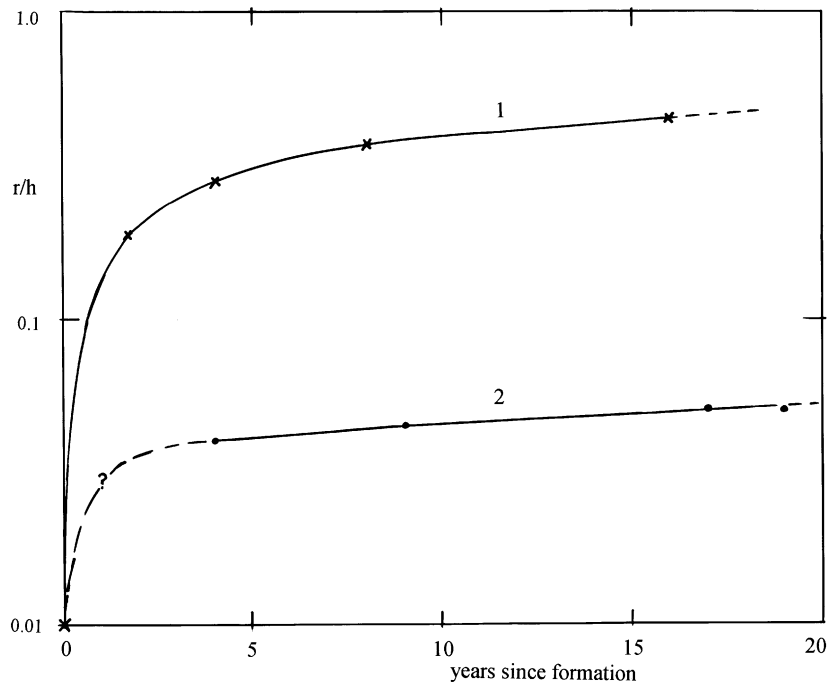


Figure 8. Normalized average crest recession rate for artificially cut slopes in chalk, plotted against log. of the number of years since their formation. 1, Weathered Upper Chalk, NE face, Overton Down ditch; 2, unweathered Upper Chalk, S face, M40 cutting (average of Points 26 and 50) (T. I. Longworth, pers. comm.)

showed that the ultimate profile had essentially been reached by then, after 32 years, with r_{ult}, from point E2, equal to *c.* 0·88 m.

In the unpublished case of the cutting for the M40 motorway through the Chiltern Hills, the cut face is not truly abandoned as the fallen debris is removed regularly from its base. Nevertheless, the behaviour of this major cutting, of 65° inclination, generally 20 to 23 m high and mainly in the lower part of the Upper Chalk, is of interest and is compared with that of the NE face of the Overton Down ditch in Figure 8. The much better performance of the M40 cutting compared to Overton Down probably results principally from its generally unweathered nature (over 20 m of the uppermost chalk was initially excavated from above the crest of the 65° cut) and its lower initial inclination.

Between its completion in 1973, and 1992, the crest of the M40 cutting has retreated by between 0·07 and 2·41 m, giving a range of retreat rates of between 3·7 and 127 mm/year (T. I. Longworth, pers. comm.). Average recessions of the faces of this cutting are given in Table I.

Table I. Average crest recession of the M40 cutting, 1973–1992

Face of cutting	Av. height h(m)	Crest recession r(m) 1973–1992	Av. recession rate (mm/year)	r/h
N (S-facing)	20·67	0·66	34·7	0·032
S (N-facing)	20·25	1·11	58·4	0·055

These figures indicate clearly the considerably greater degree of denudation on the S (N-facing) side of the cutting (T. I. Longworth, pers. comm.). Exploration of the contrasts between this case and Overton Down and of the mechanisms for this asymmetry are not pursued further here.

CONCLUSIONS

The experimental ditch in chalk at Overton Down, Wiltshire, provides a valuable record of cliff degradation in the field, against which to check available models of this process. The disadvantages of its small scale are to a considerable degree outweighed by the accuracy of the field observations.

For the best developed ditch slope before there is significant interference from the toe of the opposing scree, the agreement between the actual solid chalk profile developed beneath the debris and that predicted by the Fisher–Lehmann model is very close and that by the Bakker–Le Heux model only slightly less so. This agreement may be somewhat fortuitous, however, because of the influence of the fallen turves and the sometimes concave form of the scree slope compared to the rectilinear one assumed.

Rough field observations of the relation between free face inclination and slope crest recession lie between the assumptions made in the Fisher–Lehmann and Bakker–Le Heux models, but generally somewhat closer to the latter. Expressions for the ultimate amount of crest recession are readily obtained from the above models and yield accurate values. The rate of cliff crest recession is logarithmic after a rapid initial phase. By extrapolating from the earlier parts of the logarithmic relationship to the calculated value of the ultimate crest recession, the time required to reach this can be reliably estimated.

Although the present check on these slope degradation models is encouraging, further comparison of their predictions with field behaviour at a larger scale are clearly desirable before more general conclusions can safely be drawn.

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